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Optics damage modeling and analysis at the National Ignition Facility

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ABSTRACT

Comprehensive modeling of laser-induced damage in optics for the National Ignition Facility (NIF) has been performed on fused silica wedge focus lenses with a metric that compares the modeled damage performance to online inspections. The results indicate that damage models are successful in tracking the performance of the fused silica final optics when properly accounting for various optical finishes and mitigation processes. This validates the consistency of the damage models and allows us to further monitor and evaluate different system parameters that potentially can affect optics performance.

Keywords: Laser-induced optics damage, optics lifetime

1. INTRODUCTION

Damage analysis has been surprisingly difficult over the years, especially since the realization that statistics play a major role in the interpretation of test results. This is especially true when dealing with high-energy laser systems such as the National Ignition Facility (NIF), where final optics have beam areas exceeding 1,200 cm^2 [1] . For damage initiation studies, the key is to ensure that small-scale offline experiments sample sufficiently large areas so that their predictions are valid when applied to online optics. This is usually accomplished either through raster scan of large optics or through merging of multiple shots over several small test samples [2, 3]. For damage growth studies, this means taking multiple shots over pre-initiated sites to obtain sufficient statistics to yield the probability density of the growth behavior [4, 5]. In all instances, offline testing requires extreme care with respect to repeatability of the laser shot and sample preparation. The goal of these careful efforts is to produce damage models that can be applied to the operation of high-energy laser systems such as NIF or the LMJ (Laser MegaJoule) in France. However, as these high-energy laser systems become operational, the ability to track and monitor the damage-induced optic's lifetime becomes even more challenging because of the variety or range of operation of these laser systems (see Table 1).

Table 1. Parameter range of offline experiments vs. NIF online operation (2010-2013).

Parameter Space	Offline Experiment	NIF Operation	Units
Beam Shots	1 - 20	>100,000	-
Pulse Shapes	1	500 - 1000	-
Fluence	12	0 - 10	J/cm^2
Inspections	1 - 20	> 20,000	-
Defects per Inspection	10's	10's – 100's	-
Size Range	10 – 100's	10 – 100's	µm
Parts	1 – 5	300 - 400	-
Recycles	None	1500	-
Unique processing	1 – 2	>300	-

Table 1 illustrates some of the differences in range and variability when comparing offline experiments to actual operation of a multi-beam (192-beam) high-energy science facility such as NIF. Since NIF is a laser facility dedicated to, among others, high energy density (HED) science and ignition physics [6], it has a large operational range in terms of fluence and pulse shapes. Typical offline damage facilities, however, have only enough resources to study a few pulse shapes, and hope to use pulse scaling laws [7] to translate between offline and online pulse shapes. In addition, not all essential parameters needed for accurate damage modeling are measured; for example, NIF does not measure 3ω local fluences at all 192 beams. Furthermore, the number of optics NIF handles for its operation is staggering, especially if accounting for optics that have been recycled multiple times [8]. Unlike in an offline facility, these parts have been processed over long periods (years) and some of this optics processing could have changed, either intentionally or unintentionally. Lastly, although NIF uses an online optics inspection system called the Final Optics Damage Inspection (FODI) system [9] to measure damage in-situ, these inspections are not taken after every shot, and analysis of damage data must account for the sensitivity of the instrument which can be prone to false positives.

2. METHODOLGY

Our methodology consists of developing a dataset that uses various existing databases to capture the essence of the full shot history, as well as the processing and installation history, of all wedge focus lens (WFL) optics installed on NIF [10]. The aim of creating this dataset is to be able to evaluate the performance of each optic given everything we know of its processing and exposure. This reduces a complicated dataset of shot and processing history to a damage metric calculated for each optic. For initiation studies, we define the damage initiation metric (DIM) as the difference between the observed damage as reported by our online inspection tool and the predicted damage sites using our damage model (OpticsX) [11] over the life cycle of an optic. This dataset starts by using NIF's optics work-order database to establish the lifecycle of an optic, which is then used to collect the shot history and inspection data from other databases. The result condenses a large array of dissimilar datasets into a concise dataset that is easily managed and analyzed; we refer to this dataset as the optics performance table (OPT) [10]. For this study, we focus on NIF wedge focus lenses from 2010-2013. We describe the methodology of creating OPT as well as some of the techniques of using this dataset to analyze online damage performance.
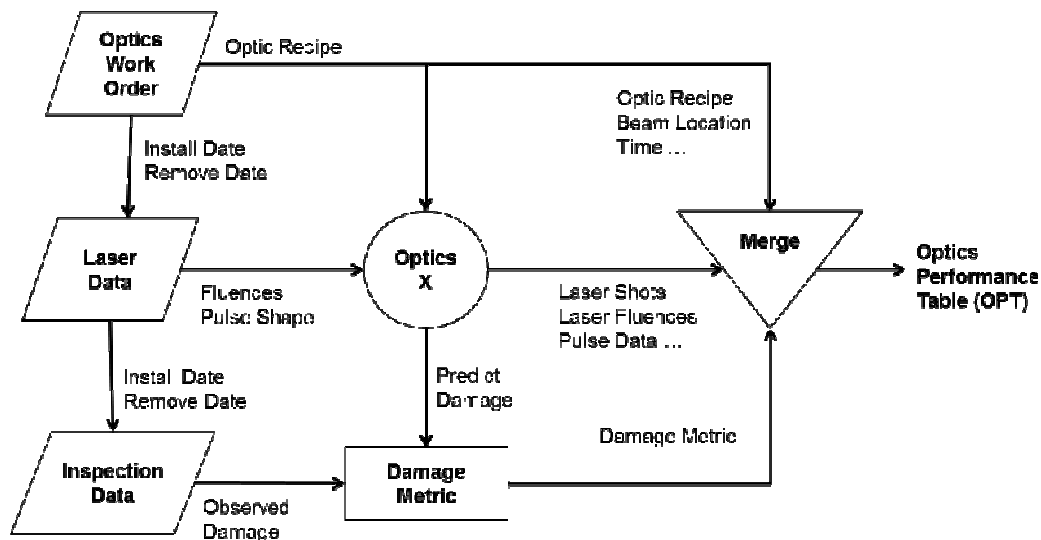

Figure 1: Flow chart illustrating the process of generating the OPT dataset

3. ANALYSIS RESULTS

Our OPT has nearly 60 parameters collected from various databases that range from optics processing to installation locations to shot history. The reason all of these fields are integrated is the inherent recognition that the real operating condition or environment of a science facility such as NIF is complicated, and there is no possibility that an offline damage testing facility can duplicate it exactly. By collecting these parameters into OPT, analysis of the optic's damage performance can find potential correlations to previously "hidden" features, which can then be carefully verified in offline testing facilities if necessary. Feature discovery is an advanced statistical technique to find previously hidden features on a dataset, and this requires the dataset to be as inclusive as possible.

In our initial analysis of WFL damage performance, we established the life cycle of the optics from the first installation to when the optic eventually was taken to be refinished [8]. This is because we had believed that most damage precursors are introduced in the grinding and polishing processing of an optic [12]. The results of >300 unique WFLs were plotted as an empirical cumulative density function (CDF) of the damage initiation metric (DIM). The DIM served to illustrate how accurate our damage model is in predicting the number of damage sites observed on a given optic (see Figure 2). A DIM of zero indicated perfect agreement of the damage model, given shot history and optic processing, with observation. A positive DIM indicated a poor performance optic, as there was more observed damage than could be accounted for using our damage model. Conversely, a negative DIM indicated a good performance optic, as there was less observed damage than expected from the damage model. Accuracy is indicated by having the peak of the distribution near zero, and precision can be inferred by measuring the spread of the distribution. It is also helpful to examine the "skewness" of the distribution, as a symmetric distribution would indicate randomness to the measurement but a positive skew could imply hidden variables not accounted for. The result of the analysis of the damage initiation metric (DIM) of the WFL (see Figure 2) show that only ~40% of the optics are within prediction results for our damage model but there is a large tail (positive skew) of optics that have many more damage sites observed than predicted (i.e., a large positive DIM).
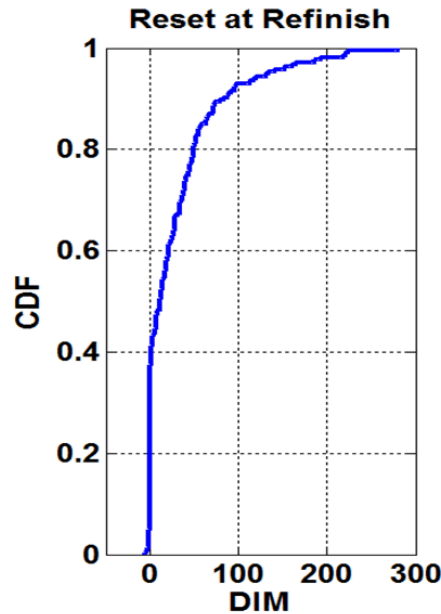

Figure 2. Cumulative density function (CDF) of the damage initiation metric (DIM) for NIF WFIs installed from 2010-2013 when the optic lifecycle is assumed to be from when first installed to when refinished.

Assembling the OPT with many parameters increases the likelihood that it could yield feature discovery if the data is analyzed correctly. One way to examine whether a "hidden variable" existed in the OPT is to use a machine learning technique such as statistical classification [13]. By assigning the various populations of the optic to different performance categories (good, poor, etc.) depending on the DIM (measured-predicted) (see Figure 3a), a classification decision tree can be constructed using supervised learning (see Figure 3b). The classification decision tree is a predicted model extracted from the training data; it is possible to use the decision tree to identify possible hidden features. In Figure 3b, the decision tree shows that the first junction depends on a variable that captures how many times the optic has been recycled (R). Furthermore, the branches for low numbers of recycles (R) leads to normal-to-great performance optics, while the branches for large numbers of recycles leads to poor performing optics. This result identifies recycling count as a potential hidden feature in optics performance – a feature not used in our damage model.
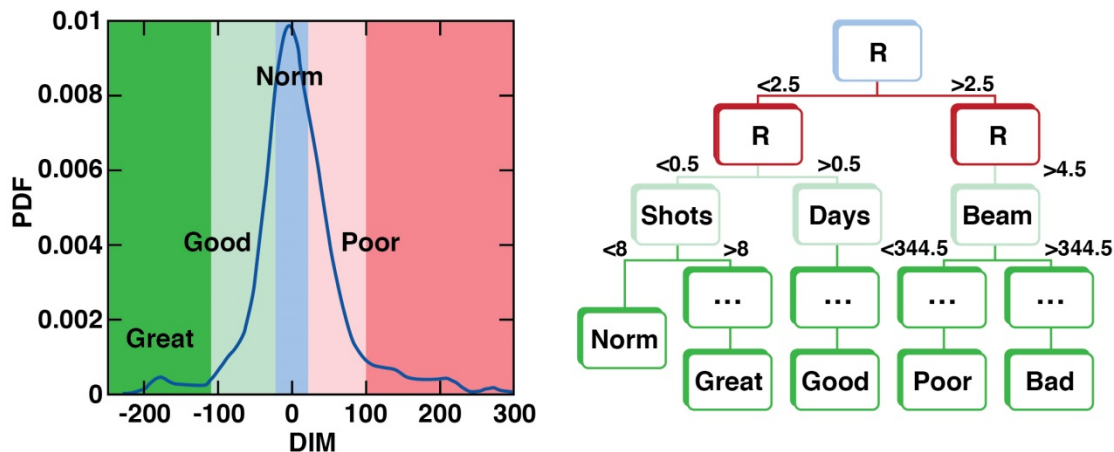

Figure 3. Schematic of assigning classifications to a damage metric PDF (left) and the classification decision tree (right) from running a supervised learning on WFLs installed on NIF using the lifecycle of first-installed to refinished.

NIF final optics such as WFLs are managed through the NIF optics recycle loop. An optic that has been installed online and has incurred damage is monitored and a limited number of damage sites are blocked to stop them from growing. When the maximum size of the damage sites reaches a threshold, the optic is exchanged and the laser damage is laser mitigated to limit its ability to grow [8, 14]. The number of recycles corresponds to the number of times the optic has been exchanged and laser mitigated. Laser mitigation consists of stripping and recoating the anti-reflected (AR) surfaces of the optic but without any grinding or polishing, which would imply that no new damage precursors would be added. The result of statistical classification, however, has established a strong correlation between the optic's performance and the number of times the optic has been recycled. This correlation can be tested by running another simulation that defines an optic's lifecycle as the time from installation online to removal for recycling. This also dramatically increases the number of lifecycles analyzed to ~1500, since a WFL optic on average has been recycled 2-3 times since 2010. The result of the simulation shows a ~40% to ~60% increase in the accuracy of population of optic lifecycles that is $\pm$ 10 from DIM =0 (see Figure 4a). In addition, the precision of the result also increases as the tail of the distribution reduces from DIM >200 to DIM<100 – this in spite of increasing the test population. Furthermore, when the damage performance is analyzed as a function of the number of times an optic has been recycled, R, there is very little difference in the optic's performance. For instance, R=0 means it was a new optic that has never been through recycling, while R>4 means the optic has been recycled at least 4 times. Figure 4b shows the mean of the DIM for optics in each recycle; although the mean DIM does seem to increase slightly, the 95% confidence interval of the mean is large enough that it can be argued that multiple recycles do not significantly affect the performance of an optic, and each recycling produces an optic that performs as if new.
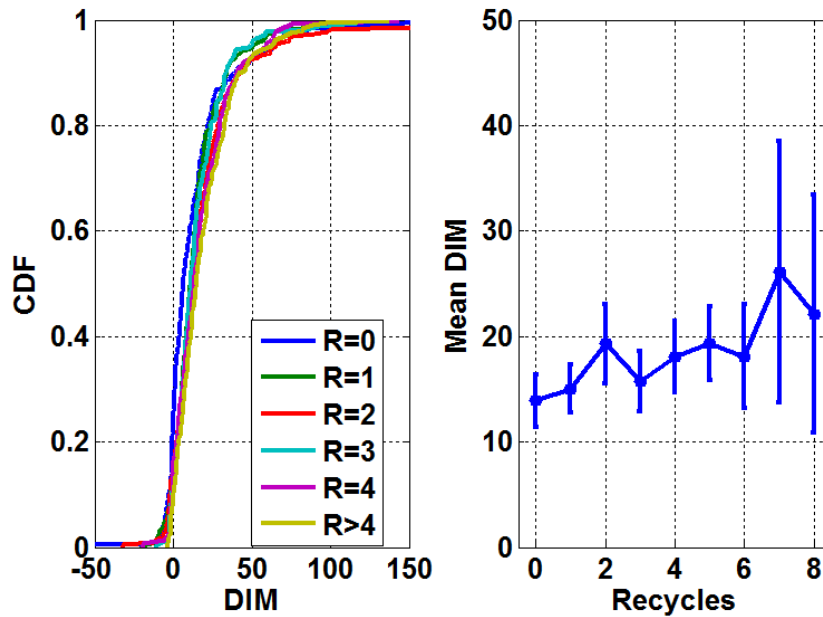
Figure 4. (4a, Left) Cumulative density function (CDF) of the damage initiation metric (DIM) for NIF WFLs installed from 2010-2013 when the optic lifecycle is assumed to be from first installed to recycling. The color plots correspond to the number of times the optic has been through recycling processes R. (4b, Right) Mean DIM vs. recycles R and the 95% confidence interval for the mean.

4. CONCLUSION

Comprehensive modeling of laser-induced damage in wedge focus lens (WFL) optics at the National Ignition Facility (NIF) has been performed. By combining processing, installation, shot, and inspection datasets along with a metric that compares the damage performance to online inspections, we have demonstrated the ability to successful validate and monitor the performance of the optics. In addition, we have shown how use of the optics performance dataset (OPT) enables the discovery and evaluation of potentially hidden features such as the role of recycling on the performance of the optic.

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